ARMY RESEARCH LABORATORY

Summary of Inductive SiC BJT Switching

by Steven L. Kaplan

ARL-TR-3678 November 2005

NOTICES

Disclaimers

Army Research Laboratory
Adelphi, MD 20783-1197

ARL-TR-3678 **November 2005**

Summary of Inductive SiC BJT Switching

Steven L. Kaplan
Sensors and Electron Devices Directorate, ARL

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
November 2005

2. REPORT TYPE
Summary

3. DATES COVERED (From - To)
October 2004 to July 2005

4. TITLE AND SUBTITLE
Summary of Inductive SiC BJT Switching

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Steven L. Kaplan

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
ATTN: AMSRD-ARL-SE-DP
2800 Powder Mill Road
Adelphi, MD 20783-1197

8. PERFORMING ORGANIZATION REPORT NUMBER
ARL-TR-3678

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Laboratory
2800 Powder Mill Road
Adelphi, MD 20783-1197

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Significant development of silicon carbide (SiC) for device applications allows its uniquely favorable properties to be exploited in circuit designs. The 4H-SiC structure has several characteristics that provide optimal speed and power handling. These include wide bandgap (3 cV), high dielectric breakdown (3.5 MV/cm), and high thermal conductivity (5 W/cm-K) [1]. By combining these properties, SiC bipolar junction transistors can achieve fast switching at high voltages (1.2 kV). New generation devices are also being developed with increased current handling capability (above 10 A). However, in order to meet the power handling requirements of FCS systems, such as hybrid-electric vehicle (HEV) power conditioning, it is necessary to configure these devices in parallel and validate their operation at high temperatures (package temperatures of 90 °C, and junction temperatures to over 150 °C). This report documents experimental characterization of SiC BJTs fabricated by CREE in various applications, including parallel switching. The results presented here indicate that SiC is well suited to meet these goals.

15. SUBJECT TERMS
Silicon carbide, bipolar, transistor, switching

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	UL	18	Steven L. Kaplan
					19b. TELEPHONE NUMBER *(Include area code)* (301) 394-3013

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Contents

List of Figures

Introduction

Several factors determine the overall power handling capability of any system that employs switching devices. These include: the device current ratings, the device gain, as well as the switching and conduction losses. The current handling for each switch in the system can be leveraged by placing devices in parallel. This is essential for power electronics applications. Silicon carbide (SiC) devices are particularly well-suited to such applications, due to their unique combination of characteristics. These include fast recovery and good voltage blocking, along with excellent high temperature performance. This should allow SiC bipolar junction (BJT) devices to operate effectively in parallel at package temperatures up to 150 °C. These device properties result from the wide bandgap (3 eV), high dielectric breakdown (3.5 MV/cm), and high thermal conductivity (5 W/cm-K) of SiC (*1*). However, the effectiveness of a parallel configuration can be compromised by unequal current sharing between devices. To evaluate the potential of SiC devices to meet the requirements of a high temperature power converter, SiC bipolar junction transistors (BJT) fabricated by CREE were packaged in parallel pair modules at ARL. Both 2 by 2 mm and 3 by 3 mm BJT devices were fabricated and evaluated. The data presented here focuses on recently delivered 3 mm by 3 mm devices, as well as older 2 mm device modules. The 2 mm devices have gains of about 10, while the newer 3 mm devices have gains above 20 and block voltages to about 1.2 kV. A Tektronix 370 curve tracer was used to measure the current gain of each BJT, for use in matching the devices as well as post-packaging measurements to determine temperature dependence. The results detailed here are being used to apply SiC BJT devices to development of an all SiC 3-phase inverter, which provides versatile power conditioning. This inverter has been demonstrated at power levels up to 10 kW.

The goal of this effort is to study the SiC devices under conditions that simulate switching of an actual motor. It is also crucial that these conditions include module temperatures up to at least 90 ^{o}C, since this is required for the mobile power conditioning applications underlying this effort. Various methods of monitoring temperature have been employed, including RTDs and thermal imaging. The RTD only gives temperature values where it is mounted, which can be 40 ^{o}C or more below the device temperature. Thermal imaging provides more accurate temperature measurement. However, the thermal camera is highly sensitive to changing emissivities of the subject materials. Methods of accounting for disparate emissivities during thermal imaging are being developed. Detailed thermal data is not presented here, but will be included in upcoming publications of results from the continued SiC device evaluation effort. Previous measurements of similar SiC BJT devices have demonstrated their excellent high power switching performance (*2*). The switching results presented here provide further evidence of the superior high current and high temperature capabilities of these devices to comparable silicon devices.

Procedure

Parallel BJT modules were switched inductively, at voltages up to 750 V and device currents up to 10 A. The addition of more parallel devices with higher gains will increase the current switching capability. In order to achieve the 10 kW power handling required, each inverter phase leg must ultimately switch 30 A (RMS). Modules corresponding to each phase leg contain multiple BJTs configured with parallel base inputs. These are matched prior to packaging so that base current sharing is maximized. The collectors of these devices are fed in common by the high power source. Measurement results (shown in figures 3 and 4) indicate excellent on-state current sharing between the devices. The emitter currents of the parallel devices were within 10% of one another for all the BJT modules tested. The most impressive results during parallel switching indicate that the individual device currents are within 3% of each other. The device current and voltage data was measured at package temperatures from 25 C to 150 C. Switching was performed up to 1 kHz and 10% duty cycle, with maximum power handling up to 4 kW per device. Figure 1 shown above, is a photograph of a parallel BJT module containing a matched pair of devices.

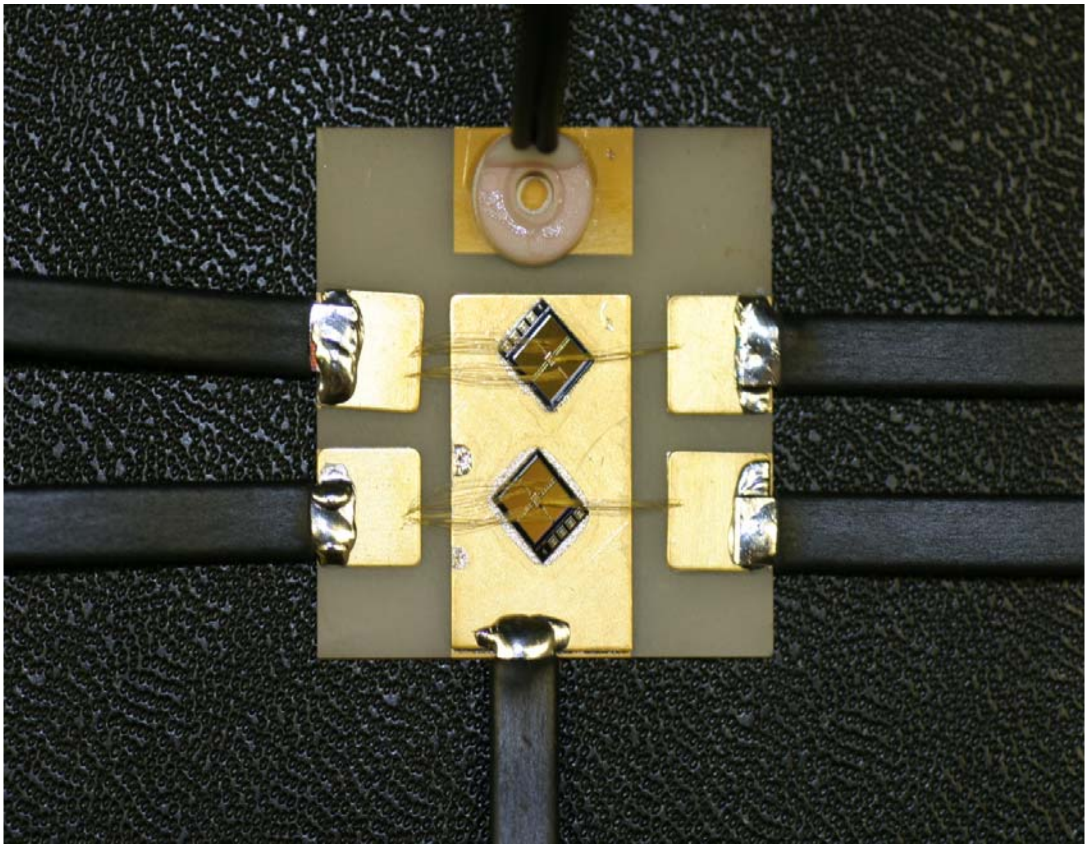

Figure 1. Test module contains a pair of silicon carbide BJT devices, mounted on a common collector pad. Parallel emitter leads extend to the left and base leads to the right. A doughnut shaped RTD to enable temperature monitoring is located above the devices.

Figure 2 is the basic inductive BJT switching circuit schematic for this experiment. The BJT indicated in this circuit actually represents the parallel pair referred to in this document. The inductance used here is nominally 4 mH, while the load was varied to produce the desired collector current values. Base current was adjusted in order to accommodate the high temperature device gains, while limiting the maximum base input to a safe level of 1.0 A per device. The on-state BJT current densities were conservatively limited to the presumed safe maximum value of 110 A/cm^2. This means, for example, that each 2 mm device can safely handle an on-state current of 4.5 A at temperatures up to 150 C, while the base currents of these devices are 1.0 A. Gain measurements of the 2 mm devices at 150 °C indicated gains of approximately 4 or 5. Therefore, the gain of these devices at high temperature is sufficient to accommodate the maximum base and collector currents. The 3 mm devices are able to handle 10 A of collector-emitter current. The high temperature gain of these devices is well above 10, so that the maximum base current is sufficient to drive them at the maximum collector-emitter current and temperature.

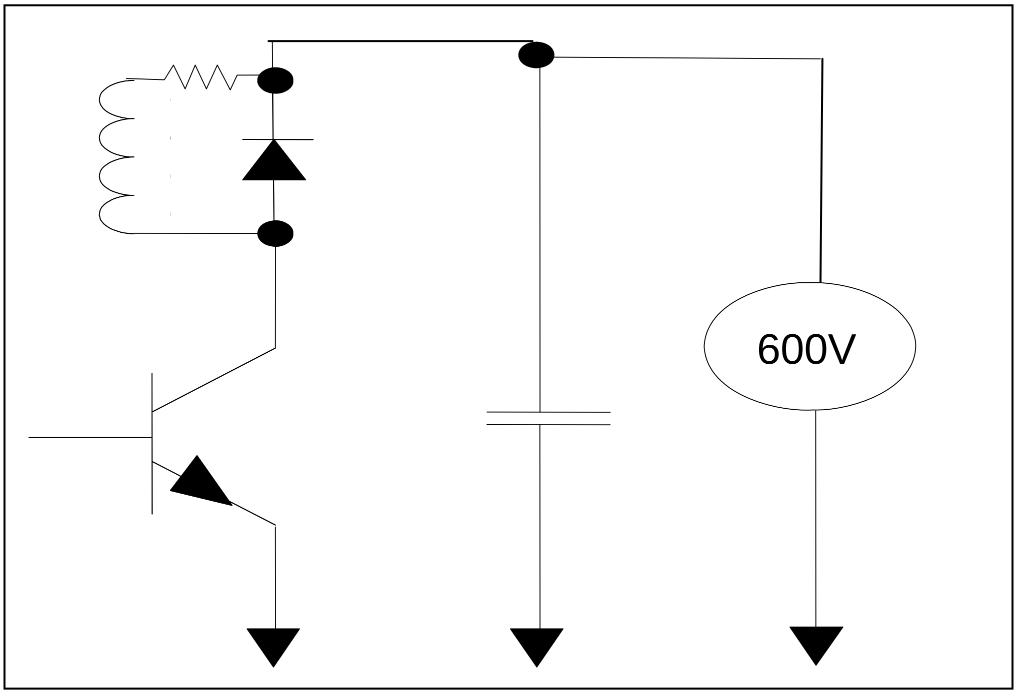

Figure 2. Inductive switching test setup.

Results

Figure 3 is an expanded view of the individual device currents for a parallel pair of 2 mm BJT devices in the inductive switching test setup. The high degree of sharing achieved by the BJT pair is clearly illustrated in this figure. Total emitter current was found to be 6.32 Amps. The on-state current of device 1 is 3.06 Amps, while the on-state current through device 2 is 3.26 Amps. This translates into 48.5% and 51.5% of the total emitter current, respectively. Other device pairs gave similar results, with current sharing within 8% for each of the four device pairs tested. Figure 4 shows the repetitive switching of the BJT device pair at 10% duty cycle. The base input pulses are 100 microseconds each, delivered at a frequency of 1 kHz. Figure 5 represent the switching losses experienced by the devices at turn-off. The devices had losses in the 700 to 850 W range during turn-off (losses during turn-on were small compared to those during turn-off.). The calculated energy loss during turn-off is below 1mJ for each device.

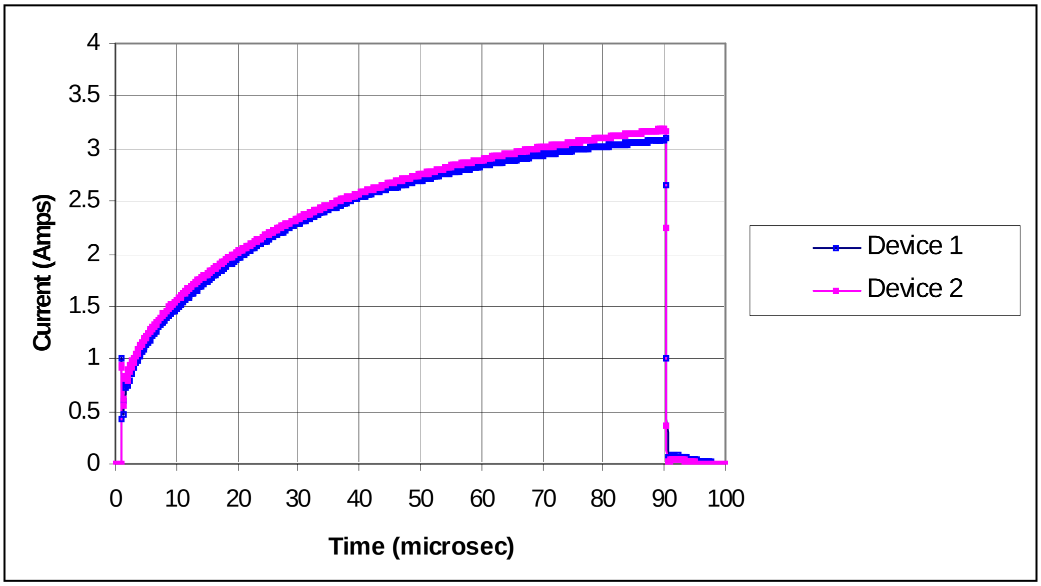

Figure 3. Current Sharing Between a Parallel Pair of 2 mm SiC BJTs at 150 °C.

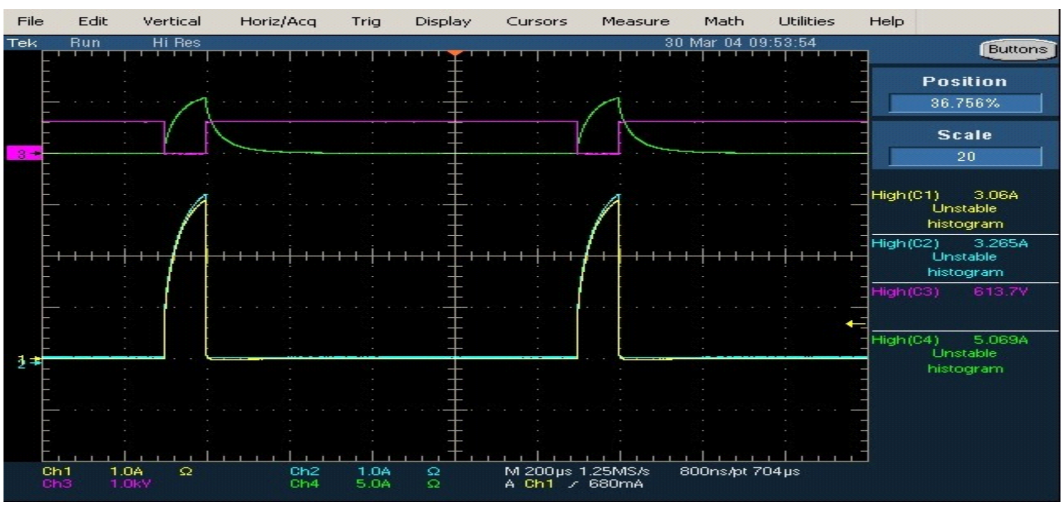

Figure 4. Oscilloscope trace showing load current and voltage (top) along with the individual emitter currents measured for a 2 mm parallel BJT pair during inductive switching.

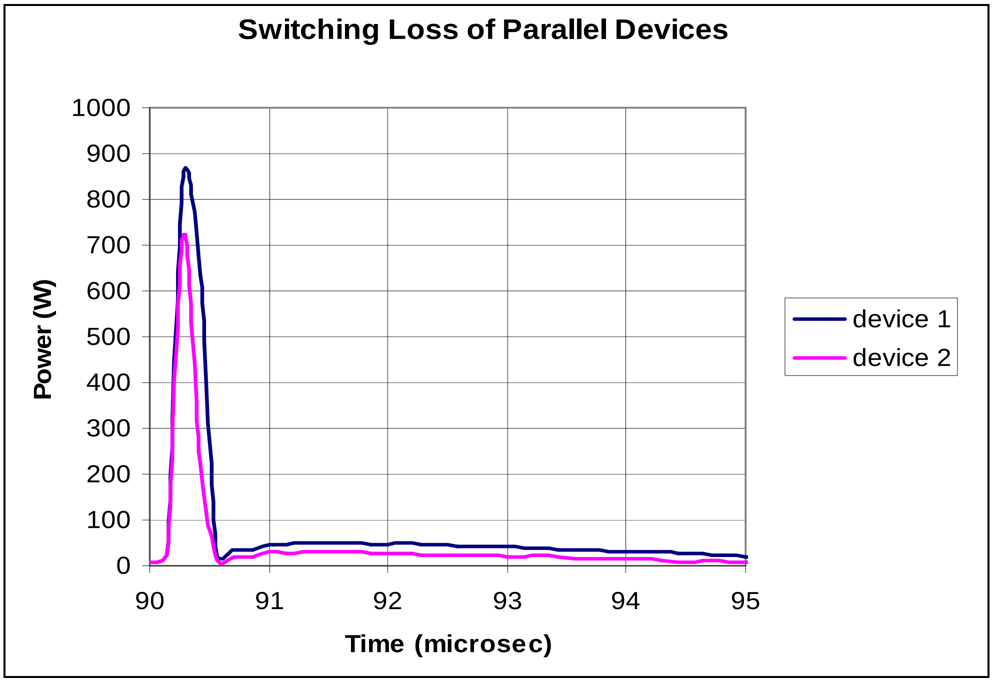

Figure 5. Switching loss during turn-off of parallel BJT pair.

Figures 6 and **7** show the transient response during inductive switching of a three device parallel module containing 3 mm SiC BJTs at 100 ^{o}C. The oscilloscope traces in these figures show the base currents, along with the total collector current and voltage at turn-on and turn-off, respectively. These data were taken while each device had a collector-emitter potential of 400 V, with 30 A total current through the module.

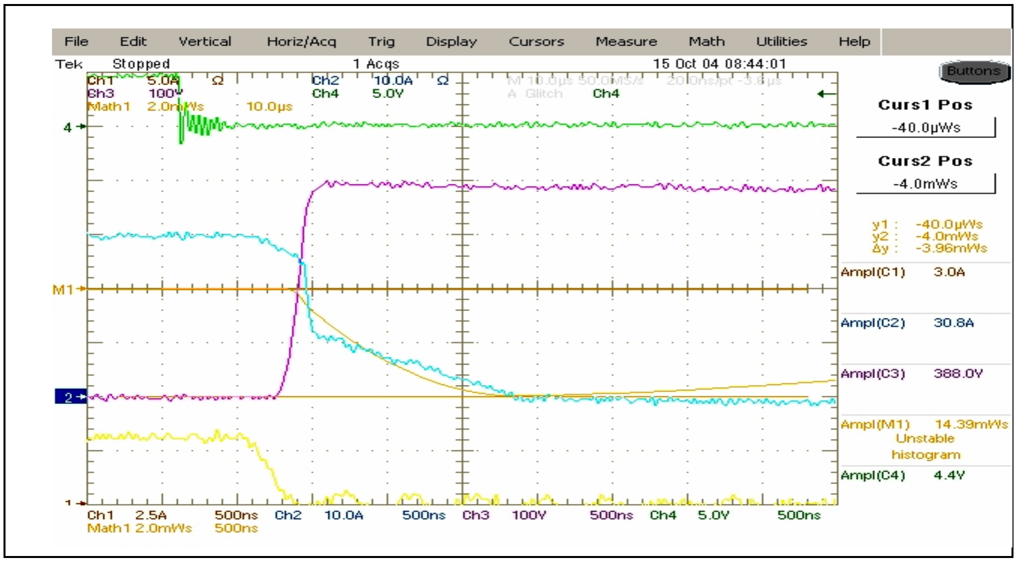

Figure 6. 400 V 100 °C turn-on.

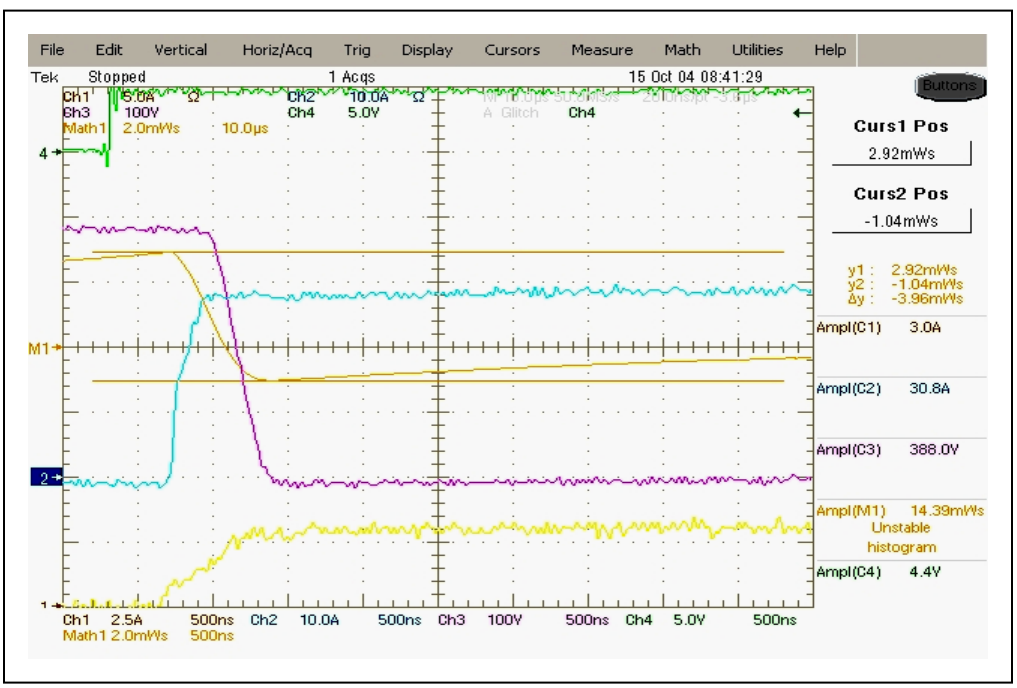

Figure 7. 400 V 100 °C turn-off.

The energies associated with turn-on and turn-off as a function of temperature, for both 300 V and 400 V, are shown in figures 8 and 9. The turn-on energies ranged from 1 to 4 mJ, while the turn-off energies were 1 to 6 mJ. The temperature dependence of these results is relatively flat, confirming the excellent high temperature performance of these BJTs in particular, as well as the expected performance of an all SiC inverter operating at a heat sink temperature of 90 ^{o}C.

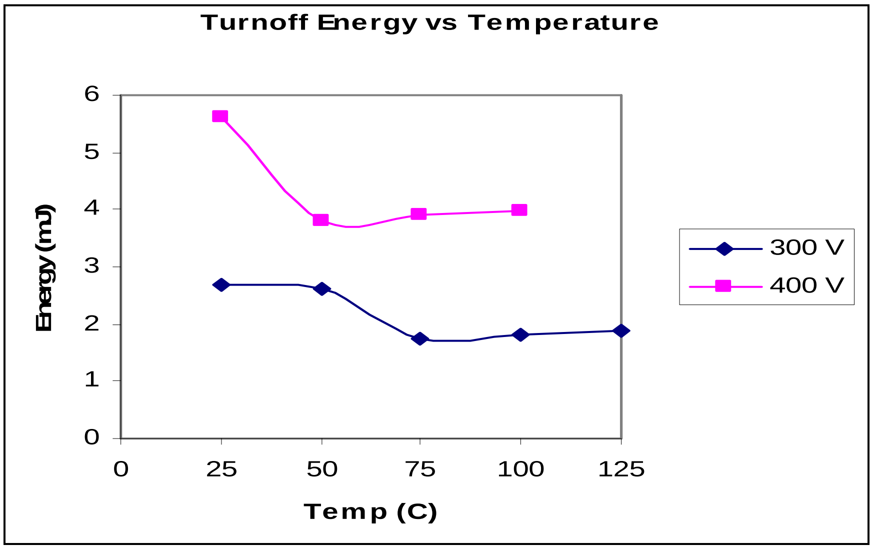

Figure 8. Energy loss during turnoff for 3 mm BJT module at 300 V and 400 V collector voltages.

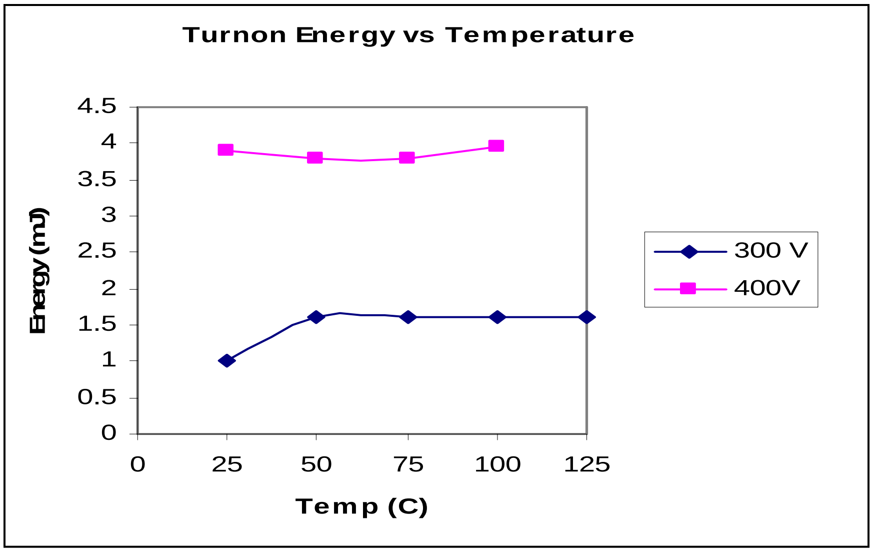

Figure 9. Energy loss during turn-on for 3 mm BJT module at 300 V and 400 V collector voltages.

Conclusions

Based on the results of these experiments, it appears that the CREE SiC BJT devices examined here effectively share current during inductive switching, and maintain this sharing at high temperature (up to a device package temperature of 150 ^{o}C). Low energy losses and power dissipations during inductive switching were indicated by the measured transient data. These results bode well for the application of these devices to the high current parallel inverter circuits necessary for power conditioning systems. The high temperature performance of these devices should allow for the flexible, portable system applications envisioned in the Future Combat Systems (FCS) program. Efforts to optimize device efficiency and high temperature performance are continuing. Experimental results will be forthcoming for the next generation of the SiC BJT devices in FY06. We are also focusing on understanding the operation and failure mechanisms of these devices. This information is used to maximize circuit performance and provided as feedback to CREE so that they can continue to improve the fabrication process for subsequent generations of devices.

References

1. Choyke, W. J.: Matsunami, H.; Pensl, G. "Silicon Carbide – A Review of Fundamental Questions and Applications to Current Device Technology," Wiley-VCH, Berlin 1997.

2. Agarwal, A.; Ryu, S.; Capell, C.; Richmond, J.; Palmour, J. W.; Phan, B.; Stambaugh, J.; Bartlow, H.; Brewer, K. "SiC BJT's for High Power Switching and RF Applications," Proceedings MRS Silicon Carbide 2002 – Materials, Processing and Devices, Vol.742, K7.3.

Distribution List

ADMNSTR
DEFNS TECHL INFO CTR
ATTN DTIC-OCP (ELECTRONIC COPY)
8725 JOHN J KINGMAN RD STE 0944
FT BELVOIR VA 22060-6218

US ARMY TACOM
ATTN AMSTA-TR-R G KHALIL
ATTN AMSTR-TR-R E BARSHAW
ATTN AMSTR-TR-R E DANIELSON
ATTN AMSTR-TR-R J WHITE
ATTN AMSTR-TR-R T BURKE
WARREN MI 48397-5000

US GOVERNMENT PRINT OFF
DEPOSITORY RECEIVING SECTION
ATTN MAIL STOP IDAD J TATE
732 NORTH CAPITOL ST., NW
WASHINGTON DC 20402

US ARMY RSRCH LAB
ATTN AMSRD-ARL-CI-OK-TP TECHL LIB T LANDFRIED (2 COPIES)
ABERDEEN PROVING GROUND MD 21005-5066

DIRECTOR
US ARMY RSRCH LAB
ATTN AMSRD-ARL-RO-EN W D BACH
PO BOX 12211
RESEARCH TRIANGLE PARK NC 27709

US ARMY RSRCH LAB
ATTN AMSRD-ARL-CI-OK-T TECHL PUB (2 COPIES)
ATTN AMSRD-ARL-CI-OK-TL TECHL LIB (2 COPIES)
ATTN AMSRD-ARL-D J M MILLER
ATTN AMSRD-ARL-SE-DP S KAPLAN (10 COPIES)
ATTN IMNE-ALC-IMS MAIL & RECORDS MGMT
ADELPHI MD 20783-1197

INTENTIONALLY LEFT BLANK.